



NACHOS: Nano-satellite Atmospheric Chemistry Hyperspectral Observation System

Presenter: Steven P. Love

PI: Steven P. Love

Team Members: Logan A. Ott, Magdalena E. Dale, Claira L. Safi, Hannah D. Mohr, Kirk W. Post, Kerry G. Boyd, James Theiler, James A. Wren, Bernard R. Foy, Arthur A. Guthrie, Nicholas Dallmann, Ryan Hemphill, C. Glen Peterson, and Manvendra K. Dubey



Program: InVEST-17-0013



NACHOS goal: High-resolution hyperspectral imaging of trace gases

Hyperspectral Imaging: Each pixel contains a high-resolution spectrum **Individual Pixel Spectra** "Pushbroom" Hyperspectral Imager 10x10⁻³ Radiance (W/[cm²sr µm]) Every spatial pixel contains a complete high-resolution Along-Slit Spatial Position spectrum Grating Atmosphere without gas plume with NO2+SO2 gas plume Wavelength Slit Detector Array Platform motion sweeps out 2nd spatial dimension 0.96 **Incoming Light** from Scene 0.94 300 350 400 450 500 Wavelength (nm) • Ground materials: mineralogy, vegetation, etc. Relatively easy; requires only modest spectral resolution and sensitivity. **Hyperspectral Data Cube (~400 MB):**

→ Atmospheric trace gases

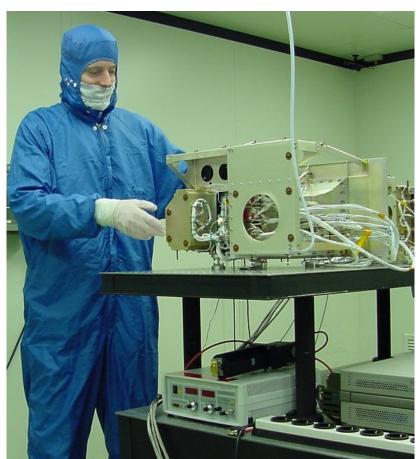
 Requires much higher spectral resolution and sensitivity. Traditionally has required a big, expensive, large-satellite instrument.



Goal is to produce a trace-gas hyperspectral imaging capability on a CubeSat platform, with eventual multi-satellite constellations



NASA Ozone Monitoring Instrument (OMI) 270-500 nm, 0.5-1.0 nm resolution 65 kg (instrument only)



LANL NanoSat Atmospheric Chemistry
Hyperspectral Observation System (NACHOS)
290-500 nm, 1.2 nm resolution, 0.6 nm sampling
4 kg (complete satellite)



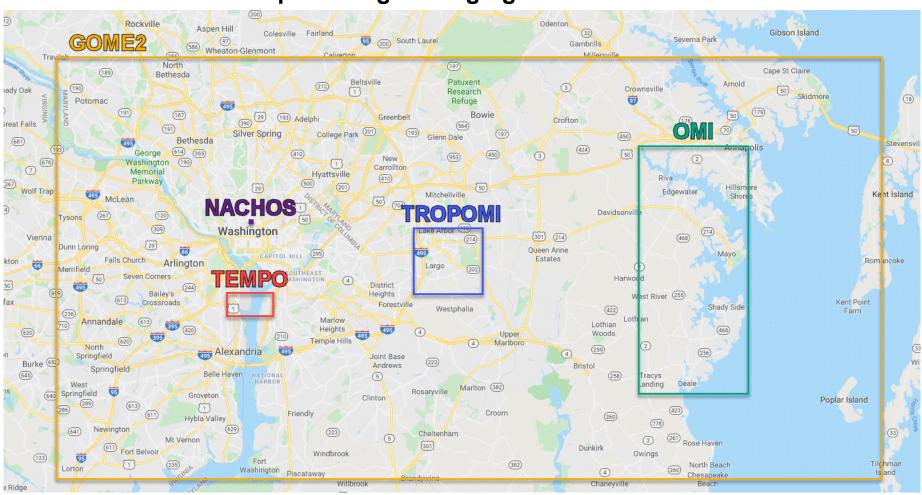






NACHOS Niche: Targeted, high spatial resolution gas imaging

Ground pixel size comparison: NACHOS *vs.* current & planned gas imaging satellite instruments



NACHOS pixel: ~0.4 km at 500 km altitude

NACHOS 350-pixel swath width corresponds to a ~140 km swath at 500 km altitude

Envisioned NACHOS constellation would provide frequent target revisits

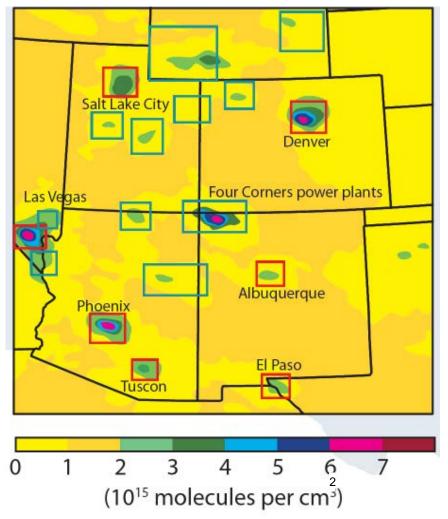






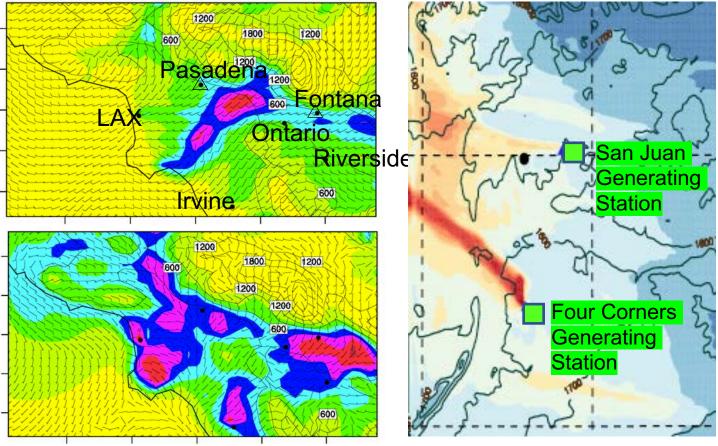
Science applications: (1) NO₂ as marker of fossil fuel burning

OMI provides regional-scale imagery:



NACHOS will provide local-scale imagery





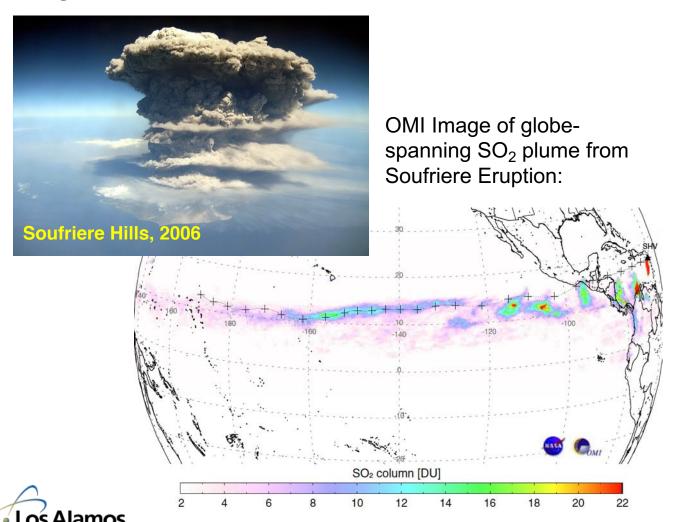
Modeled NO₂ images at roughly NACHOS spatial resolution



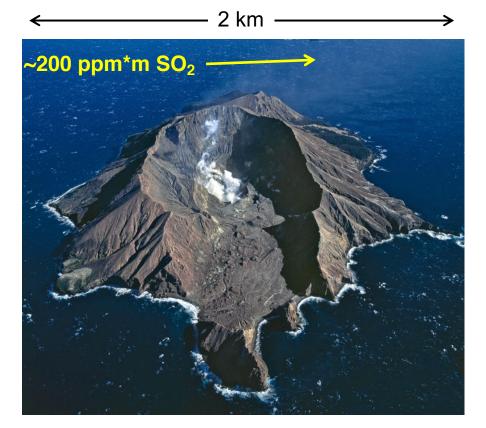


Science applications: (2) SO₂ imaging for volcanology

OMI, etc. can image SO₂ plumes from large events



NACHOS is aimed at monitoring lowlevel passive degassing at recently awakened volcanoes



Typical passive degassing (White Island, NZ)





... and many more

- Tropospheric ozone
- Formaldehyde from wildfires
- Aerosols, absorbing (black soot) vs. scattering spectrally distinguishable in this region
- Additional volcanic gases, BrO, etc.

. . .

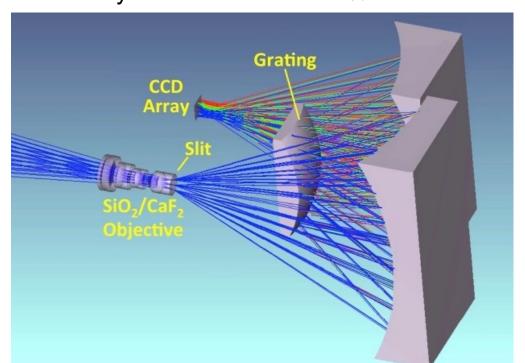




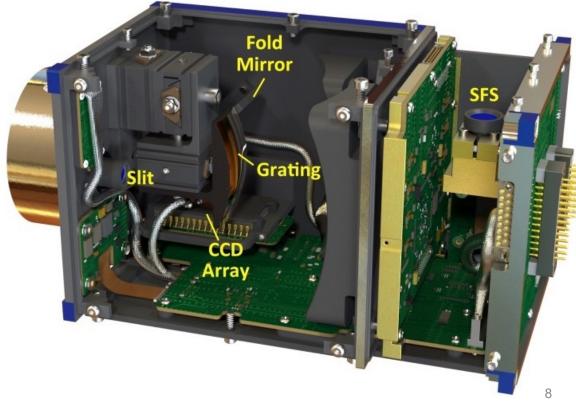
Challenge #1: Miniaturization while maintaining performance

NACHOS Hyperspectral Payload

- Offner-type hyperspectral imager with f/2.5 optics (high throughput)
- High-efficiency ruled, blazed grating (produced by Bach Research)
- Teledyne/e2v UV-optimized CCD array (updated version of array used in New Horizons LORRI instrument)
- Internal LED-based on-board calibration system provides CCD nonuniformity correction at the 0.1% level



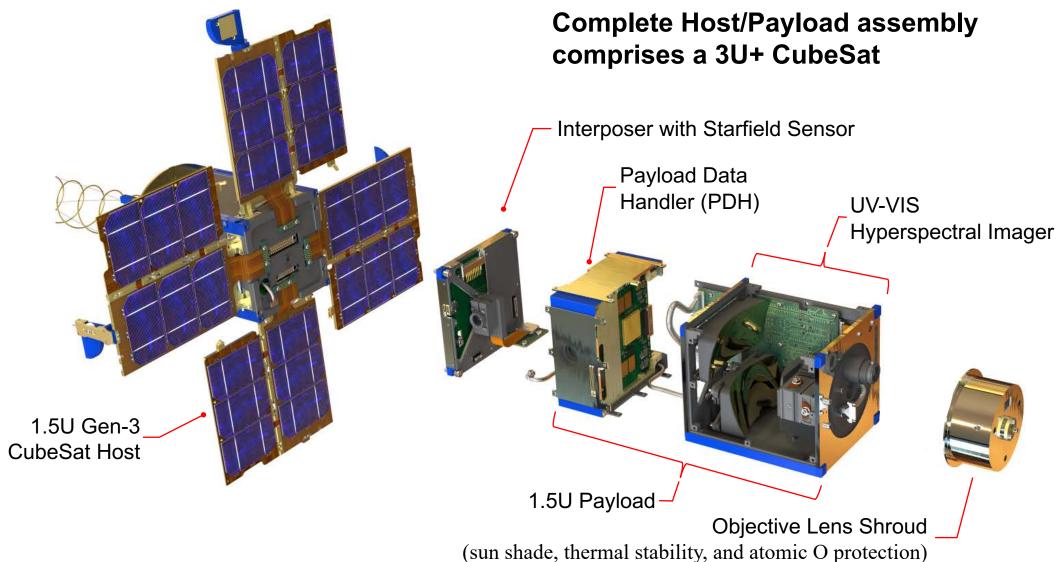
Spectrometer & Electronics comprise a 1.5U+ package







NACHOS will be a Hosted Payload on LANL's 3rd-Geneation CubeSat Bus





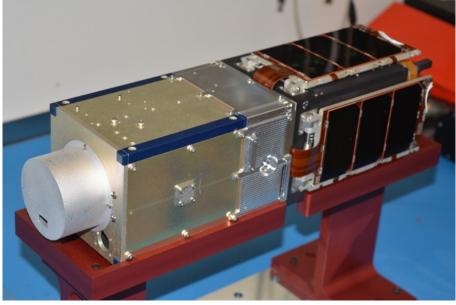


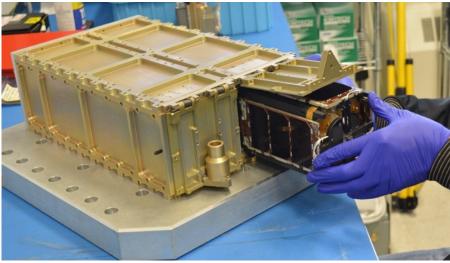


The integrated 3U+ NACHOS satellite



Los Alamos









Challenge #2: Huge raw datasets and limited downlink bandwidth

Approach:

- Perform gas-retrieval hyperspectral processing on board the CubeSat, and transmit just the processed gas-retrieval images, one for each gas of interest (a few ~1MB grayscale images vs. ~500MB raw hyperspectral data cubes)
- Also downlink some (~100 1000) representative full-spectrum pixels to perform full physics-based retrievals for absolute quantification.
- Occasionally transmit full hyperspectral cubes for system diagnostics.

Additional Challenge:

• In addition to limited downlink bandwidth, our CubeSat has relatively modest onboard processing power (216 MHz Cortex-M7 and A3P100L FPGA).

Need compact, fast, computationally efficient retrieval algorithms

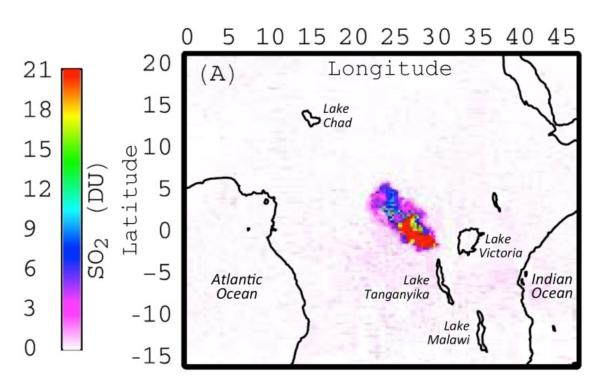




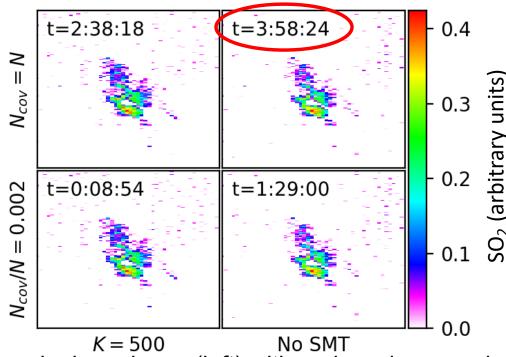
Major NACHOS Project Goal: On-Orbit validation of our streamlined onboard hyperspectral processing algorithms



Tests of LANL NACHOS Algorithms using OMI data on African volcanic SO₂ plume:

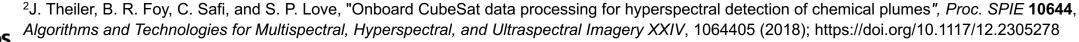


Standard ACE Algorithm: No approximations



Comparison of published retrieval¹ of the SO₂ plume from Nyamulagira volcano (left) with on-board processing results and execution times of the NACHOS Adaptive Coherence Estimator (ACE) detection algorithm² (right) for the same 320x320x1444 OMI dataset.

¹K. Yang, N. A. Krotkov, A. J. Krueger, S. A. Carn, P. K. Bhartia, and P. F. Levelt, "Retrieval of large volcanic SO2 columns from the Aura Ozone Monitoring Instrument: Comparison and limitations," *J. Geophysical Research: Atmospheres* **112**, p. D24S43 (2007).



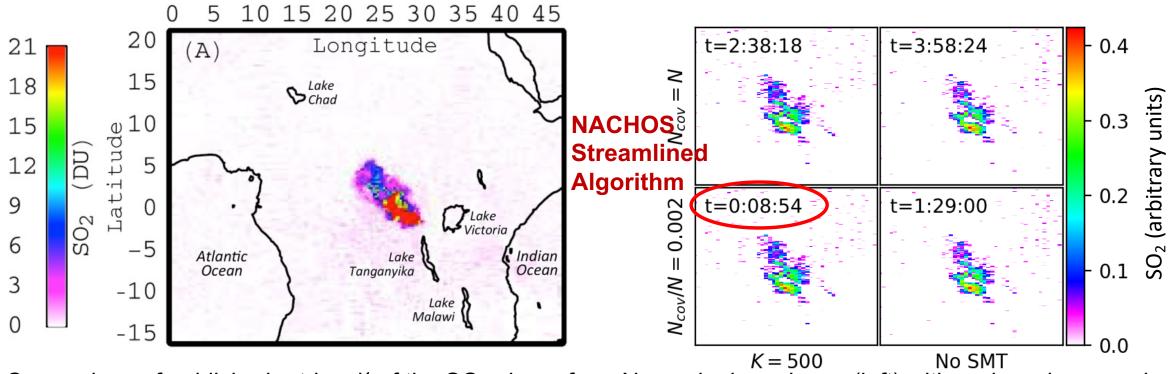




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²J. Theiler, B. R. Foy, C. Safi, and S. P. Love, "Onboard CubeSat data processing for hyperspectral detection of chemical plumes", *Proc. SPIE* **10644**, *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XXIV*, 1064405 (2018); https://doi.org/10.1117/12.2305278

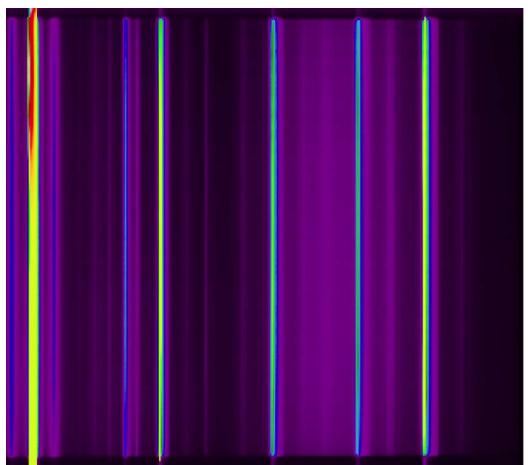




NACHOS Optical Performance: Hg emission lamp spectrum

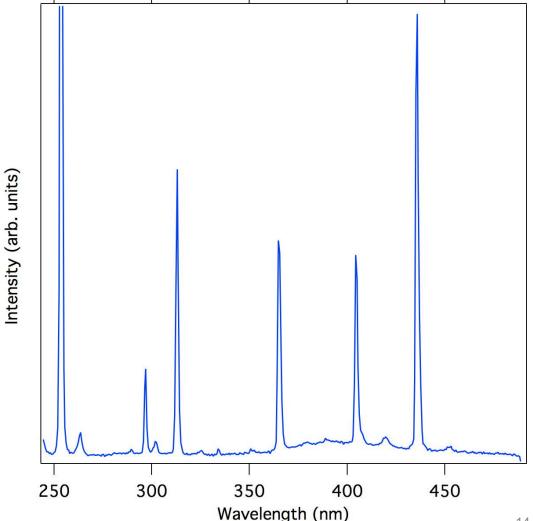
Full 2D CCD view:

• Negligible "smile" or "keystone" geometric distortion (i.e., all spectral lines straight and parallel to << 1 pixel)



Single-row spectrum:

• Instrumental linewidth (FWHM) = 2.09 pixels (1.29 nm)

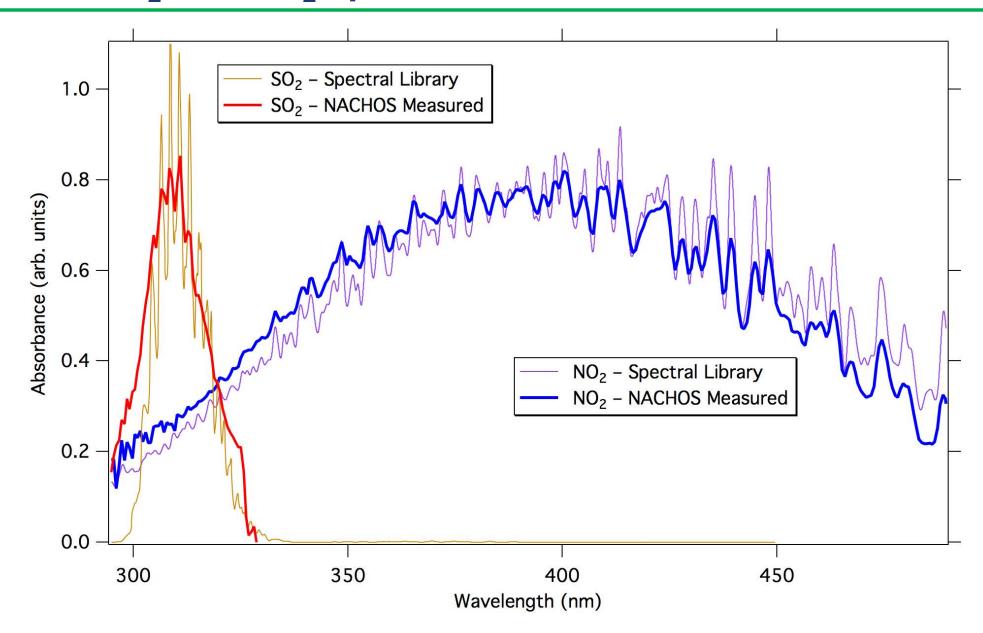








NACHOS NO₂ and SO₂ spectra









NACHOS Hyperspectral Image of Laboratory Scene

False color image using three NACHOS bands at Hg wavelengths: Red = 435.83nm, Green=404.66nm, Blue=253.65nm Resolution target bar pattern at pixel Nyquist (1 pixel/stripe) is fully resolved. Fluorescent Lamp Hg(Ar) Lamps (out of picture) 300 450 Wavelength (nm)

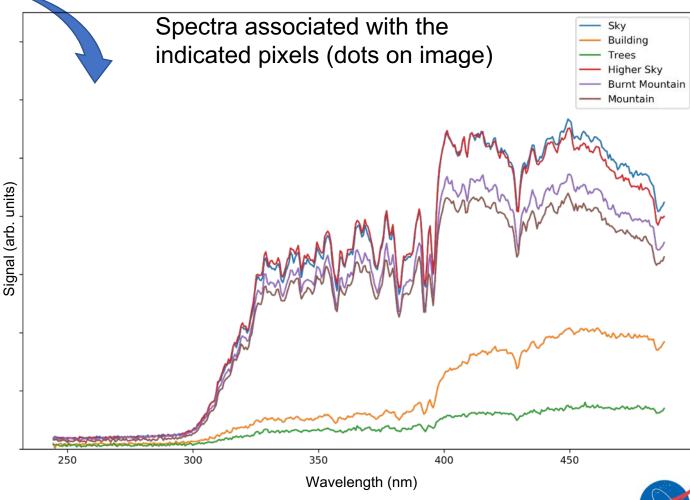




NACHOS Hyperspectral Image of Outdoor Scene

False-color image produced using NACHOS bands #20, #175, and #280 (478 nm, 383 nm, and 317 nm)





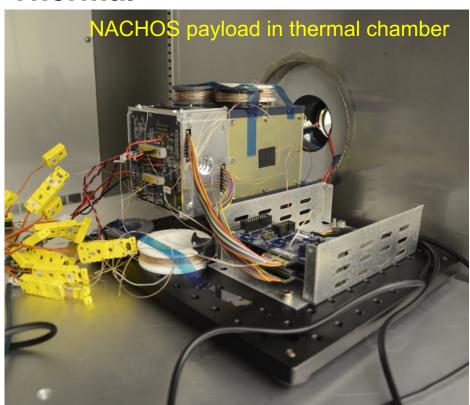






Environmental Testing of NACHOS payload

Thermal



- Multiple cycles from +30°C to -40°C, plus survival test to +60°C
- Passes tests. System remains in excellent focus throughout temperature range.

Vibration



- Multiple 3-axis shake tests conducted.
- Some mechanical issues uncovered, leading to some minor design modifications.

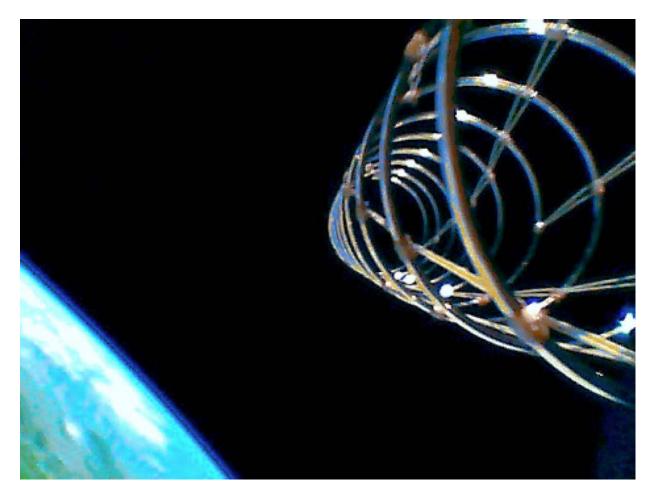






Next Steps

- Environmental testing of final qualification and flight payloads incorporating modifications based on lessons learned from previous vibration tests
- Full-system testing of integrated host/payload satellite
- Environmental testing of integrated satellite
- Launch in summer 2021 under NASA's CubeSat Launch Initiative (dependent on launch availability and schedule)
- On-orbit mission. Focus is on technology validation, but aim to do some science in the process.
- Long-term: Multi-satellite constellations, other spectral regions (VNIR/SWIR, MWIR, LWIR – more challenging), automated anomaly detection (e.g. new volcanic SO₂) and intra-constellation cueing.



View from one of LANL's Gen-3 CubeSats currently in orbit



